High-Frequency Sound Interaction in Ocean Sediments: Modeling Environmental Controls

Michael Richardson
Seafloor Sciences Branch
Naval Research Laboratory
Stennis Space Center, MS 39529-5004
Phone: (228)688-4621 fax: (228) 688-5752 email: MRichardson@earthquake.nrlssc.navy.mil

Kevin Briggs
Seafloor Sciences Branch
Naval Research Laboratory
Stennis Space Center, MS 39529-5004
Phone: (228)688-4657 fax: (228)688-5752 email: kevin.briggs@nrlssc.navy.mil

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LONG-TERM GOALS

Our long term goal is to develop accurate models for high-frequency acoustic penetration into, propagation within, and scattering from shallow water ocean sediments. This work should specifically improve the Navy's ability to detect buried mines and, in general, improve sonar performance in shallow water. Additional objectives of the NRL program are to understand and model the complex interactions among environmental processes, sediment structure, properties, and behavior. These models allow portability of high-frequency bottom interaction models to sites of naval interest.

OBJECTIVES

Provide statistical characterization of the environmental properties, especially the roughness and sediment volume properties, required to determine and model the dominant mechanisms controlling the penetration into and scattering from the seafloor of high-frequency acoustic energy. Determine the effects of biological, geological, biogeochemical, and hydrodynamic processes on the spatial and temporal distribution of sediment physical, geotechnical and geoacoustic properties at the experimental site. Develop predictive empirical and physical models of the relationships among those properties.

APPROACH

The "High-Frequency Sound Interaction in Ocean Sediments" DRI addresses high-frequency acoustic penetration into, propagation within, and scattering from the shallow-water seafloor. The primary goal of the proposed study is to understand the mechanisms for high-frequency acoustic energy penetration into sediments at low grazing angles. At present, two mechanisms are hypothesized to contribute to subcritical acoustic penetration. First, seafloor roughness diffracts energy into the sediment (Thorsos et al., 1997). Second, sediment volume heterogeneity scatters the evanescent wave energy that propagates along the seafloor interface into the sediment (Maguer et al., 2000). In order to compare the predictions of penetration of high-frequency acoustic energy into sediments based on these two hypotheses to

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14. ABSTRACT

Our long term goal is to develop accurate models for high-frequency acoustic penetration into, propagation within, and scattering from shallow water ocean sediments. This work should specifically improve the Navy???s ability to detect buried mines and, in general, improve sonar performance in shallow water. Additional objectives of the NRL program are to understand and model the complex interactions among environmental processes, sediment structure, properties, and behavior. These models allow portability of high-frequency bottom interaction models to sites of naval interest.

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actual data, seafloor roughness and the spatial variability of sediment physical and geoacoustic properties must be characterized.

If the high-frequency acoustic bottom interaction models are to be utilized outside specific experimental conditions, the effects of environmental processes (biological, hydrodynamic, geological, and biogeochemical) on the spatial and temporal distribution of properties that control propagation, scattering and penetration phenomena must be understood (Richardson and Briggs, 1996). NRL, working with other DRI investigators, quantified and are modeling these relationships. It was found that that short-term biological modification of surface roughness and long-term hydrodynamic modification of sediment morphology and roughness were the dominant environmental processes controlling seafloor properties at the experimental site. For the field experiment (SAX99), the Applied Physics Laboratory-University of Washington (APL-UW) coordinated the overall experimental design with considerable input from the other DRI scientists. APL-UW and Applied Research Laboratory-University of Texas developed the acoustic sampling strategy and the Naval Research Laboratory coordinated site selection with DRI investigators and developed an environmental sampling strategy. Also, scientists from NRL and APL-UW collaborated on measurements of sediment roughness and volume heterogeneity for use as input parameters for acoustic scattering models. For this purpose the variability of environmental measurements are examined for establishing confidence bounds on the model inputs.

WORK COMPLETED

The results from the sediment acoustic experiment (SAX99) conducted in October-November 1999 (FY00) near Destin, Florida were analyzed and interpreted with collaborators at the Applied Physics Laboratory-University of Washington. A series of papers reporting on these analyses were published in a special issue of IEEE Ocean Engineering (Eric Thorsos and Mike Richardson, guest editors) to be published in September 2002 (July issue). Six of the 13 papers devoted to SAX99 in the special issue (Briggs et al., Richardson et al., Buckingham and Richardson, Reed et al., Tang et al., Williams et al.) involved NRL investigators and addressed environmental aspects of the DRI. The environmental tasks addressed by these and other articles are:

- Characterized high-resolution (1 mm) seafloor roughness over a range of scale sufficient for determination of model input parameters for 40kHz as well as 300 kHz

- Developed, tested and conducted techniques to measure grain bulk modulus

- Analyzed and modeled sound speed and attenuation measurements in sand over the frequency range of 25-100 kHz

- Performed and evaluated resin impregnation, image analysis, and effective media modeling techniques to provide values of pore size, pore throat length, porosity, permeability, and tortuosity factor

- Characterized sediment bulk density fluctuations and derived input parameters for acoustic models from density power spectra

- Demonstrated with data-model comparisons that rough surface scattering is the dominant backscattering mechanism over the range of 20-50 kHz at the SAX99 site

- Compiled SAX99 data with previously collected sediment and acoustic data to draw conclusions on the role of sediment type in predicting backscatter strength of high-frequency acoustic energy from the seafloor

- Measured the temporal effects of biological processes of seafloor roughness on high-frequency acoustic scattering

RESULTS

Seafloor roughness was measured with stereo photography and a technique using electrical conductivity. Upon realization of series of relative seafloor height measurements, one-dimensional roughness spectra were generated and similar power-law characterizations were obtained for both methods. The higher resolution photogrammetric results, however, show a break in the power-law form from an apparent rapid decrease in roughness above spatial frequencies of 1-2 cycles/cm (beyond the resolution of the conductivity technique). Results from SAX99 demonstrate that the roughness spectra are spatially and temporally variable. The sand ripple field changed over time due to smoothing of recently generated, sharp-crested ripples by biological activity and wind-wave currents to subtle, undulating features only reminiscent of ripples. Besides temporal variance of the roughness spectra, there was a significant spatial variation in roughness features on scales of 10’s of centimeters to meters that indicated the need for larger areal coverage of future roughness measurements in order to derive representative roughness parameters for acoustic scattering models.

Sediment bulk density was measured in the medium sand at the SAX99 site with cores and density variations were measured using convention gravimetric laboratory techniques as well as electrical conductivity. The sediment density power spectra were estimated from both techniques and the spectra can be described by a power-law form (Fig. 1). The exponent of the vertical one-dimensional power-law spectra has a depth-dependence and ranges from 1.72 to 2.41. Horizontal one-dimensional spectra derived from sediment conductivity has the same form, but with an exponent of 2.2. Most of the sediment density variability is within the top 5 mm of sediments, which leads us to believe that sediment volume variability will not have major impact on acoustic scattering when the sound frequency is below 100 kHz. At higher frequencies, however, we expect sediment volume variability to play a determining role in sound scattering.

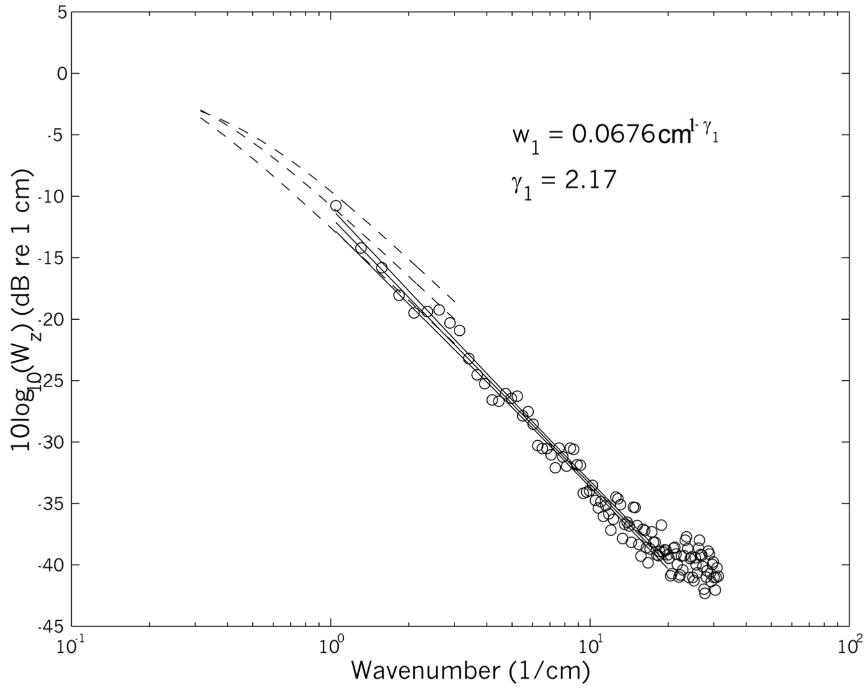

Figure 1. 1D power spectra for bulk density fluctuations sampled vertically. The dashed lines represent the spectrum and 95% confidence bounds corresponding to the bulk density fluctuations from core data. The circles represent the spectrum estimated from the sediment conductivity data and the solid lines are the power-law fit and 95% confidence bounds on the spectrum.

Porometric properties were measured and predicted for a well-sorted, medium sand using standard laboratory geotechnical methods and image analysis of resin-impregnated sediments. Sediment porosity measured by laboratory water-weight-loss methods (0.372 ± 0.0073 for mean ± 1 standard deviation) is 0.026 lower than determined by microscopic image analysis of resin-impregnated sediments (0.398 ± 0.019). Values of intrinsic permeability (m^2) determined from constant-head permeameter measurements ($3.29 \times 10^{-11} \pm 0.60 \times 10^{-11}$) and by microscopic image analysis coupled with effective medium theory modeling ($2.78 \times 10^{-11} \pm 1.01 \times 10^{-11}$) are nearly identical within measurement error. The mean value of tortuosity factor measured from images is 1.49 ± 0.09, which is in agreement with tortuosity factor determined from electrical resistivity measurements. Slight heterogeneity and anisotropy are apparent in the top three centimeters of sediment as determined by image-based porometric property measurements (Fig 2). However, the overall similarity for both measured and predicted values of porosity and permeability among and within SAX99 sites indicates sediments are primarily homogeneous and isotropic and pore size distributions are fairly uniform. The results indicate that an effective medium theory technique and two-dimensional image analysis accurately predicts bulk permeability in resin-impregnated sands.

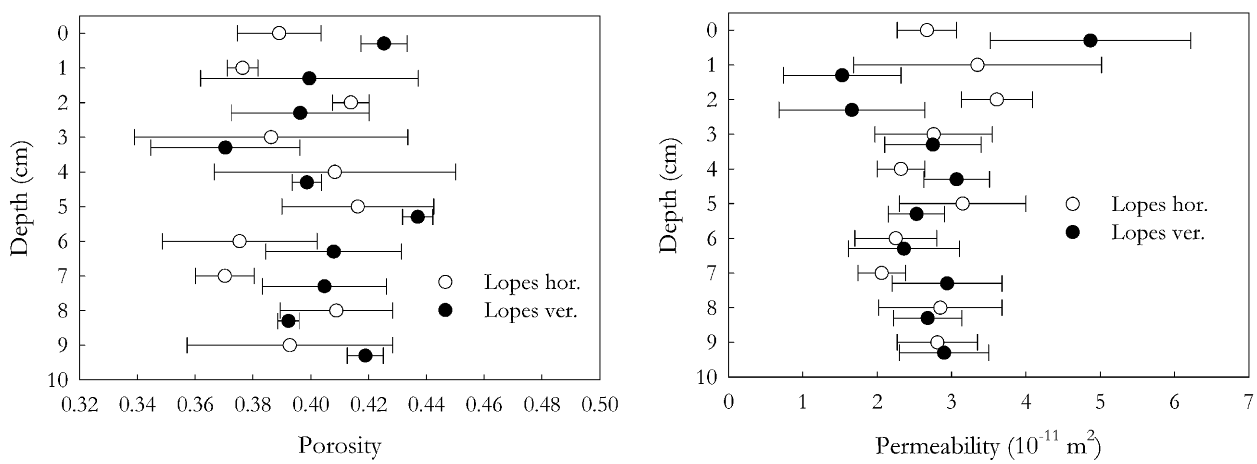

Figure 2. Image-based determinations of sediment porosity and permeability at the Lopes site at SAX99 showing heterogeneity and anisotropy, especially in the upper 2-3 cm of sediment depth.

TRANSITIONS

The results of this basic research are used in developing acoustic models for seafloor scattering. The database is potentially useful for inclusion in the NAVOCEANO shallow-water MIW sediment database.

RELATED PROJECTS

ONR's Mine Burial Processes (MBP) 6.2 program is indirectly related to this 6.1 research. Predicting burial state of mines on the sea floor is another facet of information, along with the acoustic predictions for scattering strength of seafloor targets, in the decision process in mine hunting.

Ray Lim at Coastal Systems Station, Panama City Beach, FL is involved in developing techniques for modeling acoustic scattering from buried objects, especially including the effects of sediment interface roughness in coupling acoustic energy into the sediment at subcritical grazing angles. Our characterization of the rough interface at SAX99 has a direct bearing on CSS modeling efforts.

ONR is funding Peter Jumars (UMe) and Chris Jones (APL-UW) in a high-frequency acoustic project to study the effects of benthic biological processes on backscattering. An important component of this research involves photogrammetric determination of temporal roughness variability.

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